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| **CLASSIFICATION**<br>UNCLASSIFIED | **SYSTEM NUMBER** 54679 |

**TITLE**

TACTICAL EMITTER LOCATION STUDY

**System Number:**

**Patron Number:**

**Requester:**

**Notes:**

**DSIS Use only:**

**Deliver to:** JR

88-605

# TACTICAL EMITTER LOCATION STUDY

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Final Report to

Defence Research Establishment

on Contract No. W7714-6-5147/01-ST

Scientific Authority

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August 18, 1987

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# CHAPTER 1

# FADING BEHAVIOUR

## 1.1 INTRODUCTION

In military direction finding there is a number of concerns regarding the propagation path from the transmitter to the receiver. The environment and atmospheric conditions around the DF set will have a strong influence at the strength and quality of the received signal and as such will determine the path losses associated with the direction of propagation.

Path losses are subject to temporary increases by fading. The causes may be:

1. Interference fading by multipath propagation
2. Shadow losses due to adverse atmospheric refraction, especially in the case of extended hops.
3. Atmospheric absorption losses due to very strong precipitation, in particular at very high frequencies.

## 1.2 INTERFERENCE FADING

Interference fading[1] occurs with multipath propagation. The fading depth depends upon the phase differences and the amplitude ratio of the components contributing to the received field. In radio hops where the first Fresnel zone is clear of obstruction, the ground reflection component is usually small compared with the direct-path component. When reflection occurs on the surface of water or on very smooth land surfaces, for example deserts, the direct component and the reflected component may be of approximately equal strength.

Apart from this type of multipath propagation by reflection directly on the earth's surface, additional propagation paths may be developed via tropospheric layers in which the atmospheric refraction differs considerably from the refraction which occurs in the altitude ranges below and above. Layers of this kind may be present, for example, above the direct path between transmitter and receiver antennas. However, layers near the ground may also be situated below this direct path, or the boundary of a layer may be in the altitude range between the two antennas, so that the direct path runs through this layer boundary.

As a rule, beams are curved only slightly in a tropospheric layer. Only beams entering a layer at a flat angle of incidence (below about 0.5 degrees) suffer a deflection comparable to reflection so as to form an interference field with the direct beam propagated outside this layer. It follows that radio paths which are sufficiently steep (>0.5 deg) between a high and low point enjoy basically favourable fading conditions.

Radio paths extending at moderate altitudes above the ground in a substantially horizontal direction may, in certain cases - above the valleys of rivers - be affected by layers near ground. Smooth ground layers covering large areas may form above flat ground in calm weather should the air in the high altitudes be warmer than near the ground (temperature inversion). Such exceptional conditions may prevail after sun-set when the temperature of the lower layers drops due to the cooling surface of the earth. The cold air cannot raise and the atmosphere is in a state of equilibrium. The decisive factor which affects fading is the humidity of the air in a stable inversion layer, produced by evaporation from the ground. Above wet ground, for instance above moors and rivers, the saturation limit of the air (100% relative humidity) is apt to be attained or even exceeded. Warm air absorbs more water vapour than cold air.

The refractive index of the atmosphere increases with its vapour content, i.e. its specific humidity. Thus the refractive index may rise sharply within the altitude range characterized by temperature inversion. As opposed to the normal case in which the refractive index decreases with altitude, beams within this layer are refracted upwards.

Therefore, shadow losses may be caused by refraction if one or both antennas are situated within the inversion layer or if straight line connecting the antennas intersects the boundary of the layer.

Interference may be produced although both antennas are placed at a sufficient height above the layer if part of the beam reaches the receiver antennas through the indirect path via the inversion layer. If the boundary of the layer is only a little below the direct line connecting the two antennas, the indirect paths through the layer are comparatively short. Only hops of considerable length are subject to phase conditions producing cancellation by interference. Therefore, VHF links are not nearly as much affected by interference fading above layers near the ground.

When planning UHF and SHF radio links, the first task is to investigate whether moist air layers are apt to form directly above ground; in many cases this may be ascertained by observing whether there is fog formation. The formation of smooth layers covering large areas is favored by flat ground rather than hilly territory, and they are produced more easily above constantly wet ground than above ground which is usually comparatively dry. Moreover, since layers of this kind can only form in calm weather, fading must be anticipated more often over wide, protected river valleys than above open country. In areas characterized by these layers, radio hops operating with a small angle of elevation

(< 0.5 deg.) should be avoided. Alternatively, the length of the hop should be limited to about 40 km or diversity reception employed.

## 1.3 DUCT FORMATION

Soil temperatures are subject to rapid and pronounced drops after sun-set, whereas the cooling process above large expanses of water is rather slower. In the latter case strong temperature inversion will not be caused merely by cooling. The water evaporated from the surface rises and at first, the relative humidity may rapidly decrease with altitude. The result is a marked decrease of the refractive index in the lowest altitude ranges above the water. This effect is even more pronounced near the coast where heated dry air, rising above land during the day, streams towards the sea.

The strong decrease of the refractive index with altitude favors duct formation. The bending of the beam corresponds to the earth's curvature. Beyond-the-horizon propagation occurs within such a duct and a multitude of propagation paths is produced by the reflection from the surface of the sea, which gives rise to interference fading. The duct is comparatively thin - up to about 30 meters above the surface of the water; but due to the inflow of dry air from the land, it may assume values of 50 meters or more in tropical regions. As in a waveguide waves of sufficiently short length, for instance decimetric or centimetric waves, propagate within such a duct if it is relatively thin. If the beam, on its way between the antennas, crosses the duct boundary, defocusing effects may be produced, leading to additional losses comparable in effect to shadow losses.

Apart from the above-mentioned layers forming at low altitudes above land and sea, layers may also form at higher altitudes as a result, for example, of masses of dry air descending in high-pressure areas, of advancing weather fronts, of trade winds above the oceans, or of temperature inversion within limited altitude ranges of the atmosphere. In these cases, too, multipath propagation may be caused by such layers. Since, under these conditions, reflection is caused only if the beam incidence at the boundary layer is flat, long hops will suffer more from interference fading than short ones. Here, too, the angle of elevation of the hop should exceed about 0.5 degrees.

# CHAPTER 2

# THE EFFECT OF VEGETATION ON WAVE PROPAGATION

## 2.1 INTRODUCTION

Communication by means of radio waves in forest environments is hampered by transmission losses which are substantially higher than those occuring in the absence of vegetation. Experimental investigations of propagation conditions in forests have revealed that the transmission losses may be characterized as follows.

1. For constant antenna heights, the received field varies inversely as the distance squared.
2. The presence of vegetation produces a constant loss (expressed as 'vegetation factor') which seems to be independent of the distance between the communication terminals.
3. The transmission loss is reduced by raising either the receiving or transmitting antenna. This produces a 'height-gain' effect which, when measured in decibels, varies roughly logarithmically with the antenna height.
4. The received field may be considerably depolarized, relative to the orientation of the transmitting antenna.

The first three characteristics are caused by the dissipative nature of the vegetation and possibly by that of the ground supporting it. The experimental data reported confirmed these characteristics over frequencies in the range 1-100 MHz and over distances up to 30 miles. The depolarization feature was observed at 50-100 MHz and distances up to 4 miles. This effect may be understood in terms of scattering by the vegetation; due to its conductivity, the foliage supports induced currents that tend to be randomly oriented and therefore they produce a depolarization of the overall field.

## 2.2 THE SLAB MODEL OF THE FOREST

The slab model of the forest[2] accounts for the electromagnetic properties of the vegetation. The basic slab geometry is shown in Figure 1 where the conductive slab is assumed to represent a forest with an average tree height 'h'; the plane geometry is adequate even for large distances $\rho = (x^2 + y^2)^{1/2}$, since both the sky wave and the lateral wave are only slightly affected by small amounts of curvature. The transmitter is located at a height $z_0$ above ground and is assumed to consist of a small-current element of moment Il inclined at an angle 'gama' with respect to the x-axis. The forest is characterized by the complex refractive index n given by:

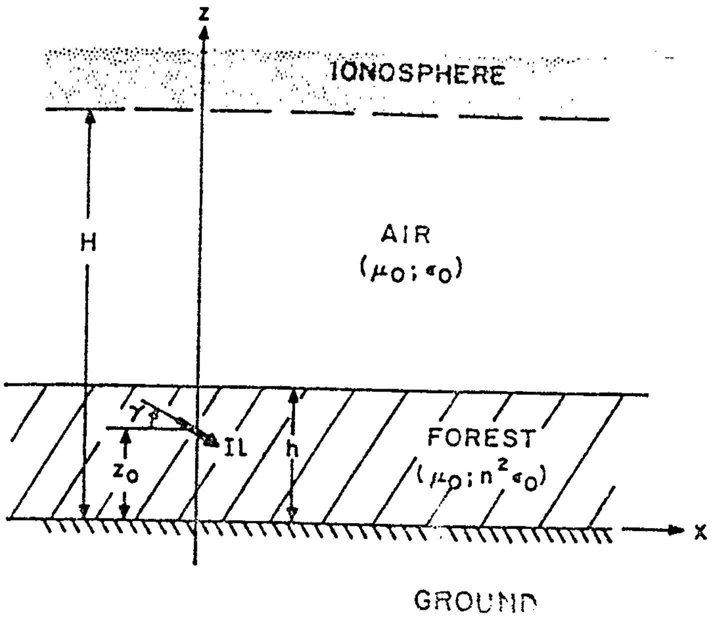

FIGURE 1: Basic geometry for the forest propagation model

$$n^2 = \varepsilon_1 - j\frac{\sigma_1}{\omega \varepsilon_o} = \varepsilon - j60\sigma_1\lambda_o$$

where $\varepsilon_1$ denotes the average relative permittivity and indicates the average conductivity of the forest medium; $\varepsilon_o$ and $\lambda_o$ are the absolute permittivity and the wavelength in air of a wave with frequency f. A time dependence exp(j $\omega$ t) is assumed and MKS units are implied unless otherwise specified.

The wavelength $\lambda_o$ must be sufficiently large if the representation of the forest in terms of a uniform, continuous medium is valid. The average separation between trees is 1-5 meters and the intervening space is usually filled with foliage and other vegetation, an upper frequency of f=100 MHz (i.e. a minimum wavelength of 3 meters) seems reasonable. The lower frequency is restricted to 1 MHz due to theoretical considerations. These considerations also prescribe a minimum range of observation $\varrho$ such that, in general, $\varrho > 1$ km. However, $\varrho$ may be considered smaller than 1 km at the higher frequencies. For practical reasons, the discussion will also be restricted to $\varrho < 100$ km since forests are not expected to preserve sufficient uniformity at longer ranges.

The forest parameters $\varepsilon_1$ and $\sigma_1$ turn out to be rather critical and only a very limited amount of data concerning their actual values are available. Certain theoretical considerations predict that $\varepsilon_1 = 1.1 - 1.2$ while sigmal is of the order of $10^{-4}$ mho/m. The ranges considered here are

$$1.01 < \varepsilon_1 < 1.5 \quad \text{and} \quad 10^{-3} > \sigma_1 > 10^{-5} \text{ mho/m}$$

Since dense forests exhibit large values for both $\sigma_1$ and $\varepsilon_1 - 1$ while thin forests yield small values for these parameters, one expects that $\varepsilon_1 - 1$ is roughly proportional to $\sigma_1$ in such a manner that the lower limits and the higher limits occur together. If it is then assumed that $\sigma_1$ is frequency independent, one obtains the approximation

$$|n^2 - 1| = |\varepsilon_1 - 1 - j60\sigma_1\lambda_o| \cong 60\sigma_1\lambda_o$$

which holds up to frequencies of 10-15 MHz.

The field in a forest model of the type considered here is primarily in the form of the lateral wave. The intensity of this field is characterized

$$|E_L| = \frac{60\ Il}{|n^2 - 1|} \cdot \frac{\exp(-\alpha_L s)}{\rho^2}$$

where

$$\alpha_L = \frac{2\pi}{\lambda_o} \text{ Im } \left( \sqrt{n^2 - 1} \right)$$

and $\alpha_L$ refers to the exponential attenuation factor produced by the presence of vegetation.

### 2.2.1 Distance Loss

The variation of the lateral wave with distance is of the form $|E_L| \cong \rho^{-2}$. Such a distance dependence produces a path loss which is greater than that of a geometric-optical variation of $\rho^{-1}$, but the larger loss is expected since the lateral wave is essentially a diffracted field. The predicted $\rho^{-2}$ variation was recently verified by extensive measurements which conclusively confirmed the $\rho^{-2}$ dependence for both polarizations within the entire range 1-100 MHz.

### 2.2.2 The Vegetation Factor

The presence of vegetation affects E. via a factor

$$F_V = |n^2 - 1| \exp(\alpha_L s)$$

since the refractive index n is a function of the forest parameters $\rho_1$ and $\varepsilon_1$. Due to the separation distance s appearing in the exponential term, the height of the vegetation above both the receiving and transmitting antennas is rather important.

It is interesting to observe that the lateral-wave model implies that the vegetation filling the space between the transmitter and receiver has no effect apart from providing a structure which guides the wave along.

### 2.2.3 The Height Gain Effect

The dependence of $E_L$ on antenna height is given by $\exp(-\alpha_L s)$. Hence, one obtains enhanced field values if the antenna elevation is increased (i.e. s is decreased). This behaviour is referred to as height gain.

The lateral-wave model yields a simple explanation for this effect since a height increase implies that the path length of the lateral wave in the lossy medium is reduced. Hence the total path loss is decreased and thus a corresponding path gain is obtained. This gain is characterized by $\alpha_1$.

There is a departure of the low-height data from the exponential variation predicted by the lateral wave and this is probably due to the effect of ground proximity, which is not accounted for in the present model. The height gain is critically dependent on the values of both $\sigma_1$ and $\varepsilon_1$, particularly at the higher frequencies. An accurate determination of both $\sigma_1$ and $\varepsilon_1$ is important for determining the total path loss in the case of tall trees and low antennas (s large).

### 2.2.4 Frequency Variation And Path Loss

The variation of the lateral-wave field E. with frequency is found by examining the vegetation factor F. since all of the other quantities do not depend on frequency. The basic path loss increases strongly with frequency even if both antennas are close to the tree tops. This situation may change if one of the antennas (or both) are sufficiently above the vegetation canopy. In that case, propagation occurs mostly by refraction or line of sight rather than via a lateral wave.

### 2.2.5 Depolarization Effects

The signal received by an antenna located in a forest is considerably depolarized with reference to the field radiated by a transmitter situated inside or outside the forest. The depolarizing effect is actually predicted by the lateral-wave model without necessitating any statistical considerations. The lateral wave in the forest is a diffracted-field contribution and need not therefore retain the polarization of the antenna producing it.

# CHAPTER 3

# DIRECTION FINDING SOFTWARE PACKAGE

## 3.1 TERRAIN GRID LAYOUT

The layout of the terrain grid is shown in Figure 2. The terrain coordinate points must be evenly spaced in the xy-plane. The spacing can be changed according to the data available. The terrain height corresponding to the xy grid points is stored in an input data file.

The program will look at the four nearest neighbours of point P, i.e. points Q1, Q2, Q3 and Q4[3]. The program will determine the direction of the steepest slope and use that slope in the direction finding calculations.

## 3.2 SOFTWARE PACKAGE

The programs described in this chapter have been written in the FORTRAN-77 language which is compatible with the IBM-PC micro-computer. The IBM-PC programing manuals should be examined prior to executing the software package. The program descriptions serve as a user manual for the depolarization software.

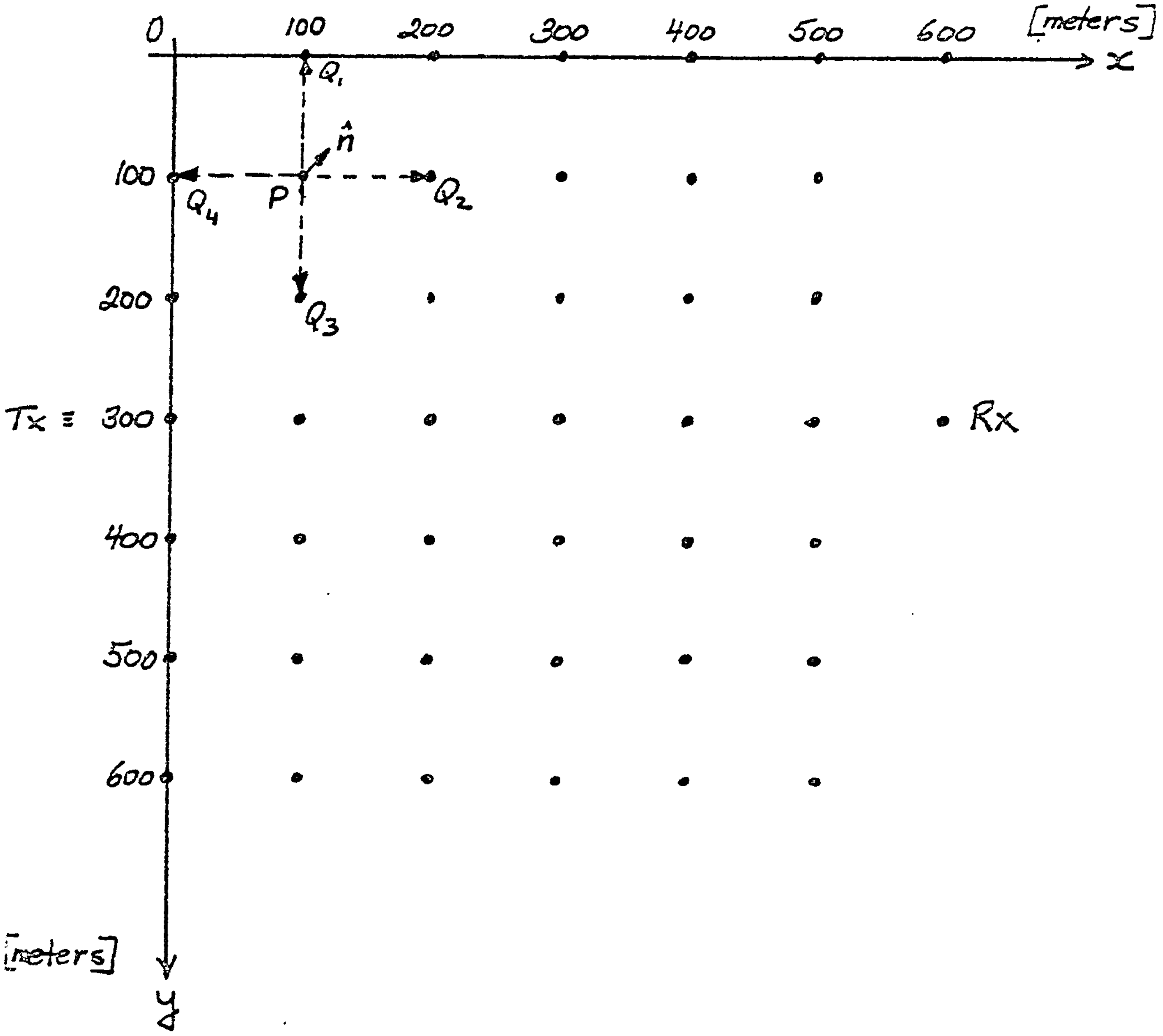

FIGURE 2: Layout of the terrain grid

## 3.3 THE MAIN PROGRAM POL

| PROGRAM NAME | DESCRIPTION |
|---|---|
| POL | Computes the composite polarization coefficient p2 at the receiver. |
| INCANG | Evaluates the angles of incidence $\Theta1$, $\Theta2$ and $\Theta3$. |
| DEPOL | Calculates the depolarization of laterally scattered waves. |

<u>PROGRAM NAME: POL</u>

The program is initialized by executing the command file POL.COM where:

| | |
|---|---|
| POL.EXE | Executive module needed for program execution. |
| POL/LIB | Library of required subroutine packages. |
| FOR001 | Logical device used for data input of the terrain's coordinate system. |

FOR005

Logical device, the terminal, used for interactive data input.

FOR006

Logical device, the terminal, used for interactive data output.

FOR007, FOR009

Logical devices used for intermediate data output, if desired.

FOR010

Logical device used for the output of the composite polarization factor p2.

## DESCRIPTION

The input variables are read from unit FOR001 in the following order: z coordinate of the DF receiver set; z coordinate of the transmitter; z coordinates of all terrain grid points under consideration where each grid point occupies one line of data.

## COMMON VARIABLES

### COMMON /DATA/

| | |
|---|---|
| XRX,YRX,ZRX | The x,y and z coordinates of the receiver. |
| XTX,YTX,ZTX | The x,y and z coordinates of the transmitter. |

### OTHER COMMON VARIABLES

| | |
|---|---|
| PI | Constant = $\lvert \cos(-1.0) \rvert$ = 3.1416... |
| WAVELENGTH | Free space wavelength corresponding to the transmitted frequency. |

## 3.4 SUBROUTINE NAME: INCANG

DESCRIPTION:

Computes the angles of incidence Θ1,Θ2 and Θ3.

INPUT PARAMETERS: (all double precision)

| | |
|---|---|
| X, Y, Z | Vector of max. length 50 containing the x-coordinate of all terrain points under consideration. |

OUTPUT PARAMETERS: (all double precision)

| | |
|---|---|
| THTA1 | The incidence angle of the transmitted wave. |
| THTA2 | The scattering angle of the reflected wave. |
| THTA3 | The azimuth angle of the reflected wave. |
| RMAG | The distance from the receiver ot the scattering point P. |

TMAG

The distance from the transmitter to the scattering point P.

## 3.5 SUBROUTINE NAME: DEPOL

DESCRIPTION:

Computes the depolarization factor p2 of laterally scattered waves.

INPUT PARAMETERS: (all double precision)

THTA1

The incidence angle of the transmitted wave.

THTA2

The scattering angle of the reflected wave.

THTA3

The azimuth angle of the reflected wave.

RMAG

The distance from the receiver ot the scattering point P.

| | |
|---|---|
| TMAG | The distance from the transmitter to the scattering point P. |
| <u>OUTPUT PARAMETERS:</u> | (all double precision) |
| p2 | The polarization factoe of the scattered wave. |
| Rpos | The Fresnel reflection coefficient for the vertical component of the polarization. |
| Rneg | The Fresnel reflection coefficient for the horizontal component of the polarization. |

# CHAPTER 4

## CONCLUSIONS AND FUTURE WORK

There is a number of mechanisms which affect the accuracy of military direction finding. Both fading and the presence of vegetation have a negative effect on direction finding.

The vegetation factor seems to be frequency independent while fading affects higher frequencies more than the lower ones. Ducting is a consideration in coastal areas where the moist ocean air meets dry air over land.

Further investigation of the effects of vegetation on wave propagation would be necessary in order to develop a comprehensive vegetation model which could be used in the direction finding routines.

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# APPENDIX A

## COMPUTER PROGRAM LISTING

```
c
    implicit real*8(a-h,o-z)
    dimension x(7,7),y(7,7),z(7,7)
    dimension rmag_array(100),tmag_array(100)
    complex*16 p2,Rpos,Rneg,p2_array(100),C2,E2pos,E2neg
    complex*16 Rpos_array(100),Rneg_array(100)
    complex*16 sum_E2pos,sum_E2neg,p2_total,dummy,sum_dummy
    common /data/ xrx,yrx,zrx,xtx,ytx,ztx
    common pi,wavelength
c
    pi = dabs(dacos(-1.0d0))
    wavelength = 3.0d+08/2.0d+08
    nout_ptr = 1
    nbig_Y   = 7
    nbig_X   = 7
c
c
c   Read in Z coordinates of terrain points
c
    do j = 1,nbig_Y
    do i = 1,nbig_X
     read(1,2003) z(i,j)
     x(i,j) = dflotj(i-1) * 100.0d0
     y(i,j) = dflotj(j-1) * 100.0d0
    end do
    end do
c
c   Process the terrain point data
c
    do j = 2,nbig_Y-1
    do i = 2,nbig_X-1
c
    inumber = i
    jnumber = j
c   Compute the angles of incidence 'thta1,thta2,thta3'
    call incang(inumber,jnumber,x,y,z,thta1,thta2,thta3,rmag,tmag)
c
c
c   Compute the depolarization factor 'p2'
    call depol(thta1,thta2,thta3,rmag,tmag,p2,Rpos,Rneg)
```

```
c
c
   p2_array(nout_ptr)   = p2
   rmag_array(nout_ptr) = rmag
   tmag_array(nout_ptr) = tmag
   Rpos_array(nout_ptr) = Rpos
   Rneg_array(nout_ptr) = Rneg
c
   nout_ptr = nout_ptr + 1
c
   end do
   end do
c
   do i = 1,nout_ptr-1
   write(7,2001) i,p2_array(i),Rpos_array(i),Rneg_array(i),
   1rmag_array(i),tmag_array(i)
   end do
c
c  Summate contributions of all scattering points under consideration
c
   sum_dummy = dcmplx(0.0d0,0.0d0)
   sum_E2pos = dcmplx(0.0d0,0.0d0)
   sum_E2neg = dcmplx(0.0d0,0.0d0)
   nn = nout_ptr - 1
   do i = 1,nn
    C1 = 2.0d0 * pi /((tmag_array(i)+rmag_array(i)) * wavelength)
    C2 = dcmplx(0.0d0,-C1)
   E2pos=(Rpos_array(i)*exp(C2))/(rmag_array(i)*tmag_array(i))
   E2neg=(Rpos_array(i)*exp(C2))/(p2_array(i)*rmag_array(i)*tmag_array
    dummy = E2pos/E2neg
    sum_dummy = sum_dummy + dummy
    sum_E2pos = sum_E2pos + E2pos
    sum_E2neg = sum_E2neg + E2neg
   write(9,2001) i,dummy,sum_dummy
   end do
c
   p2_total = sum_E2pos/sum_E2neg
   write(9,2002) p2_total
c
2000 format(f8.2,1x,f8.2,1x,f8.2)
2001 format(i5,1p8d12.4)
2002 format(1p8d12.4)
2003 format(f8.2)
2004 format(2i5,1p8d12.4)
c
   stop
   end
```

```
      subroutine incang(i,j,x,y,z,thta1,thta2,thta3,rmag,tmag)
c
c     This subroutine evaluates the incidence angles thta1,thta2
c     and thta3
c
      implicit real*8(a-h,o-z)
      dimension x(7,7),y(7,7),z(7,7)
      common /data/ xrx,yrx,zrx,xtx,ytx,ztx
c
c
c     The co-ordinates of terrain points in the following order :
c     P(I=1),Q1(I=2),Q2(I=3),etc.
c
       a1   = x(i,j) - x(i,j-1)
       a2   = y(i,j) - y(i,j-1)
       a31  = z(i,j) - z(i,j-1)
       a32  = z(i,j) - z(i,j+1)
       a3   = (a31 + a32)/2.0d0
       amag = dsqrt(a1*a1 + a2*a2 + a3*a3)
c
      b1   = x(i+1,j) - x(i,j)
      b2   = y(i+1,j) - y(i,j)
      b31  = z(i,j) - z(i-1,j)
      b32  = z(i,j) - z(i+1,j)
      b3   = (b31 + b32)/2.0d0
      bmag = dsqrt(b1*b1 + b2*b2 + b3*b3)
c
      c = 1.0d0
c
c     Compute the cross product axb to get the surface normal sn
c
      v1 = c*(a2*b3 - a3*b2)
      v2 = c*(a3*b1 - a1*b3)
      v3 = c*(a1*b2 - a2*b1)
      vmag = dsqrt(v1*v1 + v2*v2 + v3*v3)
c
      an1 = v1/vmag
      an2 = v2/vmag
      an3 = v3/vmag
c
c     Angle delta determines the amount of deviation of the surface
c     normal from the z-axis.
c
      delta = dacos(an3)
c
c     Vector R is from point P to the receiver.
c
      r1 = xrx - x(i,j)
      r2 = yrx - y(i,j)
      r3 = zrx - z(i,j)
      rmag = dsqrt(r1*r1 + r2*r2 + r3*r3)
c
c     Dot product of n with r will yield angle thta2.
c
      thta2 = dacos((r1*an1+r2*an2+r3*an3)/rmag)
```

```
c
c   Vector T is from point P to the transmitter.
c
    t1 = xtx - x(i,j)
    t2 = ytx - y(i,j)
    t3 = ztx - z(i,j)
    tmag = dsqrt(t1*t1 + t2*t2 + t3*t3)
c
c   Dot product of n with t will yield angle thta1
c
    thta1 = dacos((t1*an1+t2*an2+t3*an3)/tmag)
c
c   Compute angle thta3(see report for details)
c   r22 and r11 are part of a new coordinate system
c
c   Express vector q as nxt
c
    q1 = an2*t3 - an3*t2
    q2 = an3*t1 - an1*t3
    q3 = an1*t2 - an2*t1
    qmag = dsqrt(q1*q1 + q2*q2 + q3*q3)
c
    r22 = (q1*r1+q2*r2+q3*r3)/qmag
c
    sum1 = r1 * (an2*an2*t3 - an2*an3*t2 - an3*an3*t1 + an1*an3*t3)
    sum2 = r2 * (an2*an3*t3 - an3*an3*t2 - an1*an1*t2 + an1*an2*t1)
    sum3 = r3 * (an1*an3*t1 - an1*an1*t3 - an2*an2*t3 + an2*an3*t2)
c
    r11  = (sum1 + sum2 + sum3)/qmag
c
    thta3 = datan2(r22,r11)
c
c
1001 format(1p10d12.4)
1002 format(2i5)
c
    return
    end
```

```
      subroutine depol(thta1,thta2,thta3,rmag,tmag,p2,Rpos,Rneg)
c
c     This routine will calculate the depolarization of
c     laterally scattered waves.
c
      implicit real*8(a-h,o-z)
      complex*16 Erc,Y,Rpos,Rneg,pol1,pol2,p2,E1,CON
      common pi,wavelength
c
      RTD  = 180.0d0/pi
      DTR  = pi/180.0d0
c
c     p1       = polarization of the incident wave
c     p2       = polarization of the scattered wave
c     R+,R-    = Fresnel reflection coefficients
c     thta1    = Incident angle wrt. z-axix
c     thta2    = Scattering angle wrt. z-axis
c     thta3    = Azimuth angle of the scattered wave
c     B1,B2,G  = angles related to the scattering geometry through
c                thta1,thta2 and thta3
c
c     Compute the complex Fresnel reflection coefficients
c     The relative permitivity Er
      Er     = 81.0d0
c     The Conductivity 'sigma'
      sigma = 5.8d+07
c     The relative permeability Ur
      Ur     = 2.3d0
c
c     The Dielectric constant Erc
      E2   = 60.0d0 * wavelength * sigma
      Erc  = dcmplx(Er,E2)
c
      E1   = Erc/Ur
      Y    = sqrt(E1)
c
c     The Fresnel coefficients
      CON   = Y * Y - dsin(thta1) * dsin(thta1)
      Rpos  = (Y*Y*dcos(thta1)-sqrt(CON))/(Y*Y*dcos(thta1)+sqrt(CON))
      Rneg  = (dcos(thta1)-sqrt(CON))/(dcos(thta1)+sqrt(CON))
c
c     Polarization ratio of the incident wave
      p1 = 1.0d+15
c
c     Polarization of the scattered wave
c     Angles in Degrees
      thta1deg = thta1 * RTD
      thta2deg = thta2 * RTD
      thta3deg = thta3 * RTD
c
      bet    = dcos(thta1)*dcos(thta2) - dsin(thta1)*dsin(thta2)*dcos(thta
      beta   = dsin(thta2)*dsin(thta3)/dsqrt(1.0d0 - bet*bet)
      betadeg = RTD * beta
c
      beta2 = dacos(dcos(beta)*dcos(thta3)
```

```
   1     - dsin(beta)*dcos(thta1)*dsin(thta3))
   beta2deg = RTD * beta2
c
   if(betadeg.ge.90.0d0) then
      betadeg = 89.99d0
         beta = betadeg * DTR
   end if
c
   if(beta2deg.ge.90.0d0) then
      beta2deg = 89.99d0
         beta2 = beta2deg * DTR
   end if
c
c  Introduce the limiting cases
c  beta = pi/4.0d0
c  beta2 = beta
c
   pol1  = p1 * (Rneg * dtan(beta)*dtan(beta2) + Rpos)
   pol1  = pol1 - Rneg*dtan(beta) + Rpos*dtan(beta)
c
   pol2  = Rneg + Rpos * dtan(beta)*dtan(beta2)
   pol2  = pol2 - p1*(Rneg*dtan(beta2) - Rpos*dtan(beta))
c
c  Polarization ratio of the scattered wave
   p2 = pol1/pol2
c
c
1001 format(1p10d12.4)
c
   return
   end
```

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5. DATE OF PUBLICATION (month and year of publication of document)

18 AUGUST 1987

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

30

6b. NO. OF REFS (total cited in document)

7

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W7714-6-5147/01-ST

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